

# Results on Charm Baryon Spectroscopy from Tevatron Study of $\Lambda_c(2595)$ , $\Lambda_c(2625)$ , $\Sigma_c(2455)$ and $\Sigma_c(2520)$ Baryons

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on behalf of the CDF Collaboration

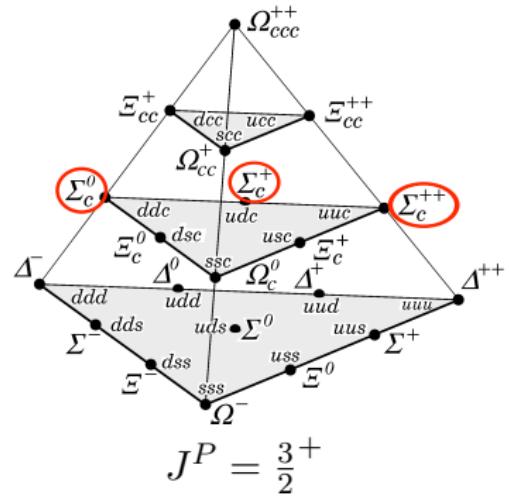
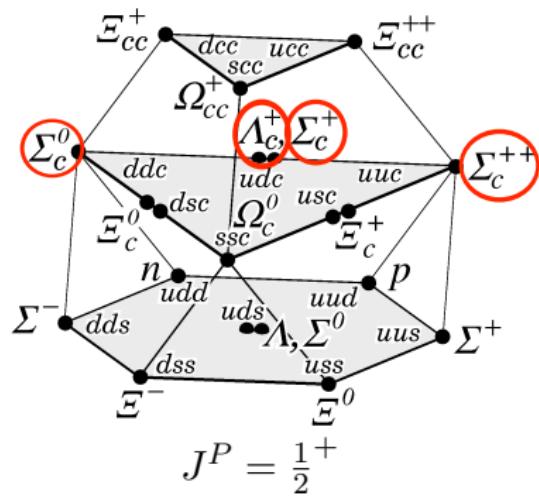
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# Charm Baryons

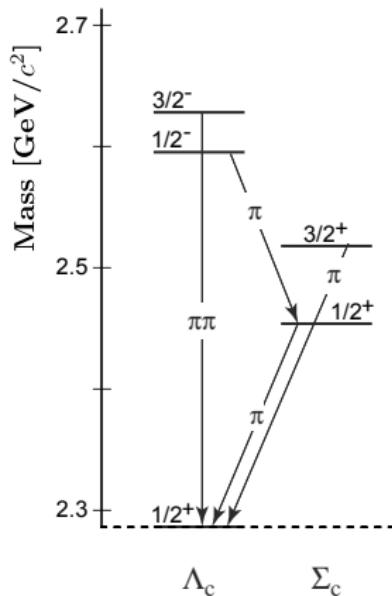


- $\Lambda_c^+ (J^P = \frac{1}{2}^+)$  charm baryon with smallest mass  $\rightarrow$  weak decay
- $\Sigma_c(2455) (J^P = \frac{1}{2}^+)$ ,  $\Sigma_c(2520) (J^P = \frac{3}{2}^+)$ 
  - $\Lambda_c^+$  spin excitations: spin-1 light diquark
  - isospin triplets  $\Sigma_c^0$ ,  $\Sigma_c^+$ ,  $\Sigma_c^{++}$
  - strong decay to  $\Lambda_c^+ \pi^{-,0,+}$



# $\Lambda_c^+$ Orbital Excitations ( $l = 1$ )

$\Lambda_c(2595)^+ (J^P = \frac{1}{2}^-)$  and  $\Lambda_c(2625)^+ (J^P = \frac{3}{2}^-)$



- isospin singlets  $\rightarrow$  decay to  $\Lambda_c^+ \pi^+ \pi^-$
- nonresonant decays via  $P$ -wave (parity conservation in strong interaction)
- resonant decays  $\Lambda_c(2595) \rightarrow \Sigma_c(2455) \pi$  via  $S$ -wave
- resonant decays  $\Lambda_c(2625) \rightarrow \Sigma_c(2455) \pi$  via  $D$ -wave (angular momentum and parity conservation)
- resonant decays to  $\Sigma_c(2520) \pi$  kinematically disfavored



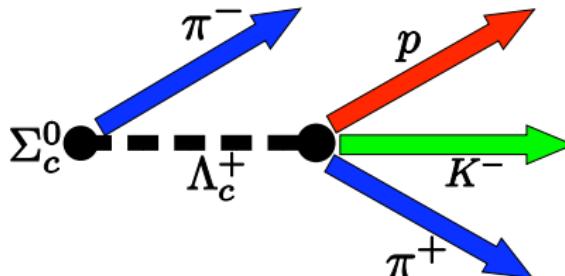
# Motivations

- study of  $P$ -wave charm mesons pioneered by ARGUS and CLEO
- enough CDF data for analogous high statistics studies in charm baryon system
- charm baryon system testing ground for heavy quark symmetry
  - rich mass spectrum
  - relatively narrow widths of the resonances
- improvement of previous mass and decay width measurements of  $\Sigma_c(2455)^{0,++}$ ,  $\Sigma_c(2520)^{0,++}$ ,  $\Lambda_c(2595)^+$  and  $\Lambda_c(2625)^+$
- proper inclusion of kinematical threshold effects in  $\Lambda_c(2595)^+ \rightarrow \Sigma_c(2455)^{0,++} \pi^{+-}$
- direct experimental determination of pion coupling constant  $h_2$  in chiral Lagrangian
  - knowledge of  $h_2$  provides information about other excited charm and bottom baryons
  - up to now calculated using measured  $\Gamma(\Lambda_c(2595)^+)$



# Selection Method

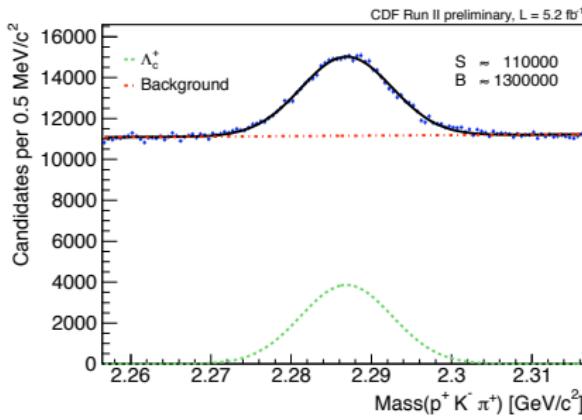
- Hadronic Trigger requires two displaced tracks with  $p_T > 2 \text{ GeV}/c$  (selection of secondary vertex decays)
- use integrated luminosity of  $5.2 \text{ fb}^{-1}$
- application of neural networks (NeuroBayes)
  - $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$   
lifetime, vertex fit, particle identification, Dalitz structure
  - $\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \pi^{-,+}$ ,  $\Lambda_c^{*+} \rightarrow \Lambda_c^+ \pi^+ \pi^-$   
 $\Lambda_c^+$  network output, vertex fits
- look at mass difference distributions to remove  $\Lambda_c^+$  mass resolution



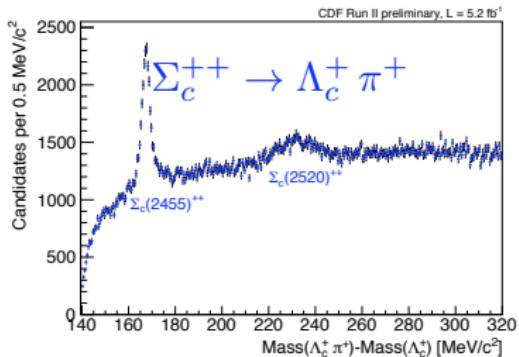
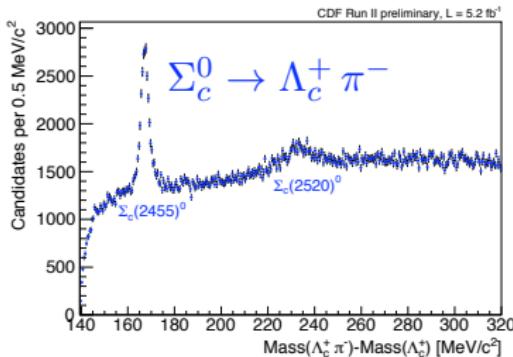
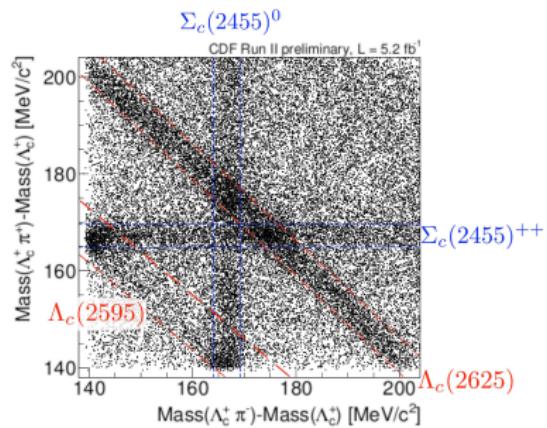
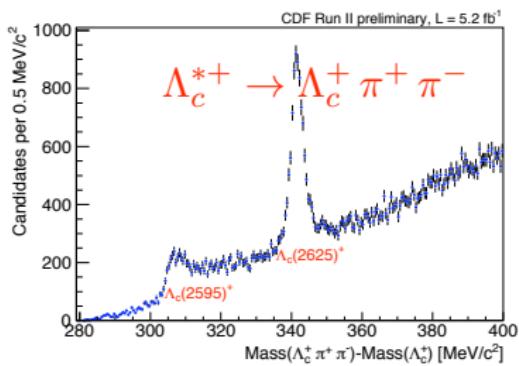
# Network Trainings

- trainings solely based upon real data by means of  $s\mathcal{P}lot$  weights  
→ independent of simulated events
- $s\mathcal{P}lot$  technique corresponds to advanced sideband subtraction
- invariant mass as discriminating variable between signal and background → requires significant signal in mass spectrum

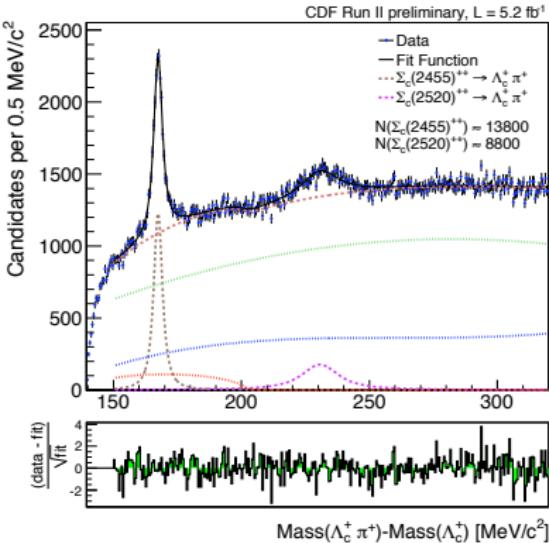
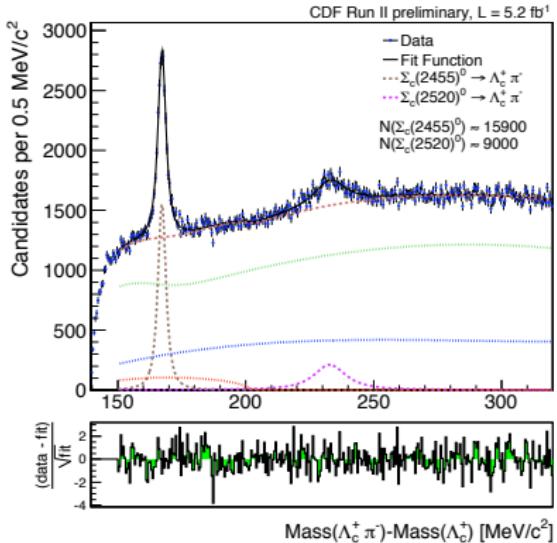
candidates used for  $\Lambda_c^+$  training:



# Resulting Spectra



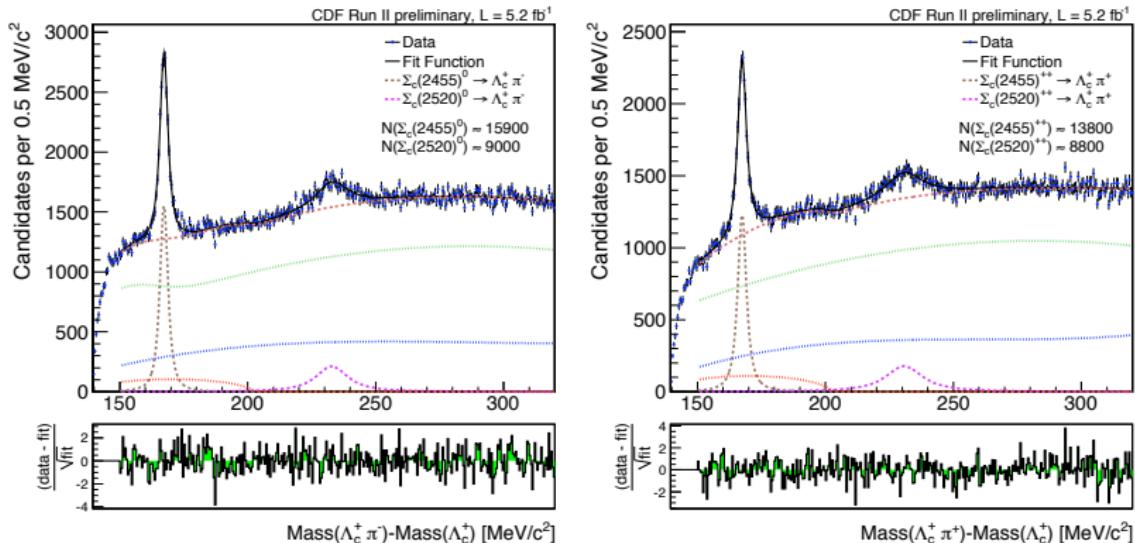
# Fit Strategy



- binned maximum likelihood method
- signals: convolutions of nonrelativistic Breit-Wigner functions with detector resolutions ( $\approx 2 \text{ MeV}/c^2$ )
- several background constituents



# $\Sigma_c(2455)^{0,++}$ and $\Sigma_c(2520)^{0,++}$ Fits

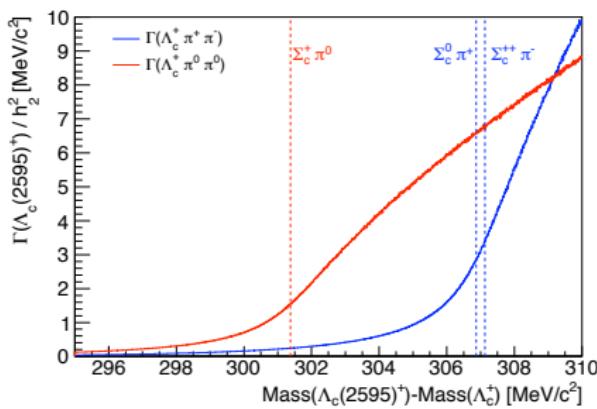


- combinatorial background without real  $\Lambda_c^+$
- real  $\Lambda_c^+$  combined with random track
- feed-down from  $\Lambda_c(2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$



# $\Lambda_c(2595)^+$ Line Shape

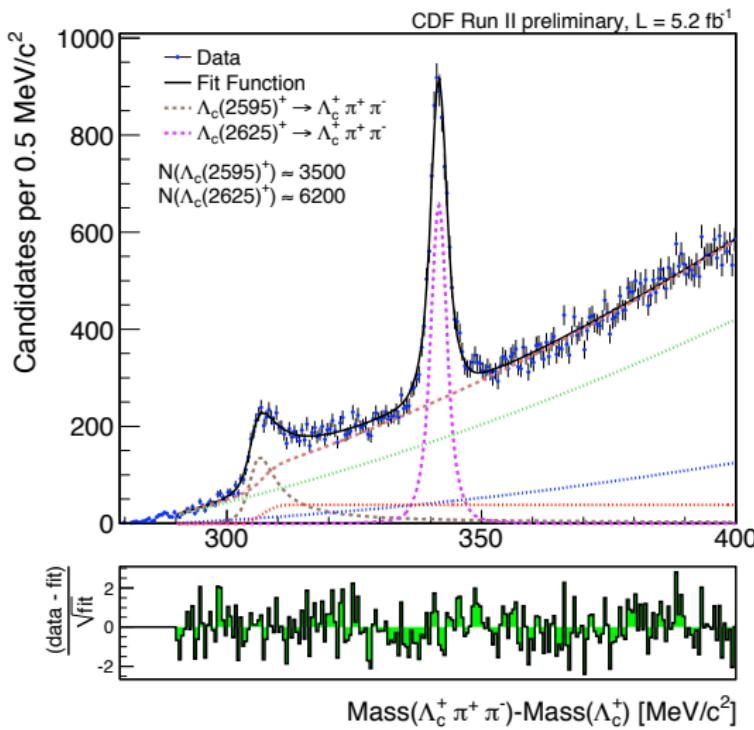
$\Lambda_c(2595)^+ \rightarrow \Sigma_c(2455)^{0,++} \pi^{+-}$  right at kinematical threshold  
⇒ Breit-Wigner shape strongly distorted by threshold effects  
→ calculation of mass-dependent width:



- Blechman *et al.*:  
Threshold effects in excited charmed baryon decays,  
*Phys. Rev. D* 67, 074033
- $h_2$ : pion coupling constant in  
 $\Lambda_c(2595) \rightarrow \Sigma_c(2455) \pi$   
→ can be determined from data



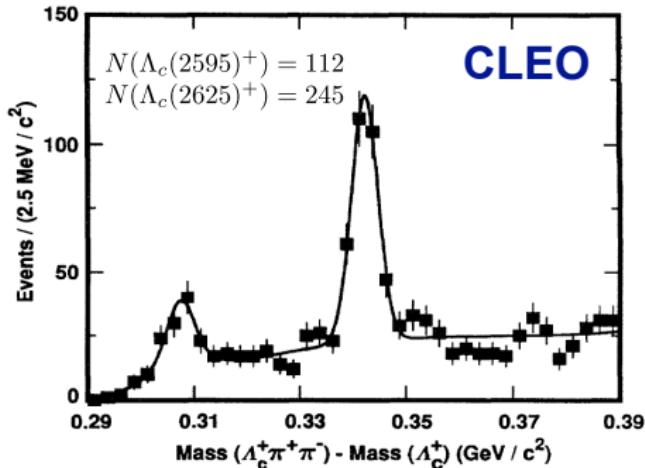
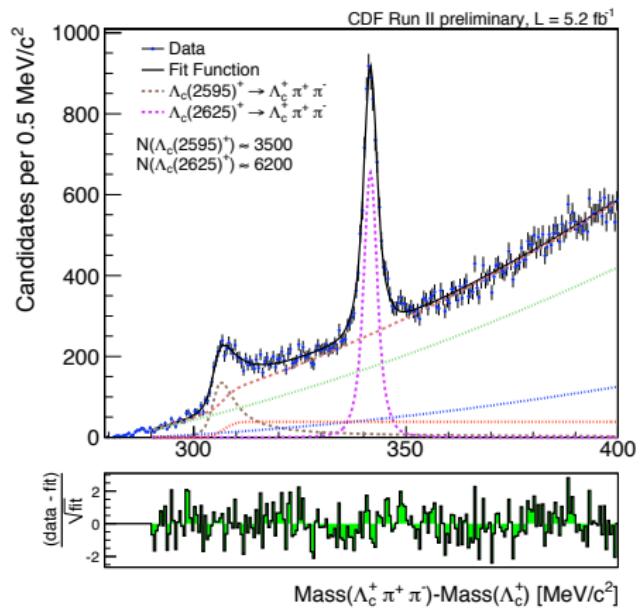
# $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ Fits



- combinatorial background without real  $\Lambda_c^+$
- real  $\Lambda_c^+$  combined with two random tracks
- $\Sigma_c(2455)^{0,++}$  combined with random track



# Comparison with CLEO Measurement



# Systematic Uncertainties

- detector resolutions
  - uncertainties on the Monte Carlo simulations
  - affect all decay widths
- overall mass scale
  - magnetic field and energy loss uncertainties in momentum scale calibration
  - affect all masses and decay widths
- fit models
  - possible biases because of signal-background correlations
  - affect  $\Sigma_c(2520)$  properties
- external input for  $\Lambda_c(2595)$  signal shape
  - uncertainties on PDG values of  $\Sigma_c(2455)$  mass differences and decay widths
  - affect  $\Lambda_c(2595)$  properties



# Results

analysis provides 12 measurements (PDG values in parentheses):

	$m - m(\Lambda_c^+)$ [MeV/ $c^2$ ]		$\Gamma$ [MeV/ $c^2$ ]	
$\Sigma_c(2455)^0$	$167.28 \pm 0.12$	$(167.30 \pm 0.11)$	$1.65 \pm 0.50$	$(2.2 \pm 0.4)$
$\Sigma_c(2455)^{++}$	$167.44 \pm 0.13$	$(167.56 \pm 0.11)$	$2.34 \pm 0.47$	$(2.23 \pm 0.30)$
$\Sigma_c(2520)^0$	$232.88 \pm 0.46$	$(231.6 \pm 0.5)$	$12.51 \pm 2.28$	$(16.1 \pm 2.1)$
$\Sigma_c(2520)^{++}$	$230.73 \pm 0.58$	$(231.9 \pm 0.6)$	$15.03 \pm 2.52$	$(14.9 \pm 1.9)$
$\Lambda_c(2595)^+$	$305.79 \pm 0.24$	$(308.9 \pm 0.6)$	$2.59 \pm 0.56$	$(3.6^{+2.0}_{-1.3})$
$\Lambda_c(2625)^+$	$341.65 \pm 0.13$	$(341.7 \pm 0.6)$	$< 0.97$ (90%CL)	$(< 1.9)$

- $h_2^2 = 0.36 \pm 0.08$
- combined statistical and systematic uncertainties
- discrepancy in  $\Lambda_c(2595)$  mass compared to previous measurements due to proper treatment of kinematical threshold effects, data consistent



# Summary

- mass difference and decay width measurements of the charmed baryons  $\Sigma_c(2455)^{0,++}$ ,  $\Sigma_c(2520)^{0,++}$ ,  $\Lambda_c(2595)^+$  and  $\Lambda_c(2625)^+$
- analysis with highest number of signal events
- considerable improvements in precision of  $\Lambda_c(2595)$  and  $\Lambda_c(2625)$  properties
- proper inclusion of kinematical threshold effects in  $\Lambda_c(2595)$  decay
  - significantly smaller measured value of the  $\Lambda_c(2595)$  mass
  - direct measurement of the pion coupling constant  $h_2$
- after bottom and charm mesons as well as bottom baryons CDF now also studies charm baryons

[http://www-cdf.fnal.gov/physics/new/bottom/100701.blessed-Charm\\_Baryons/cdf10260\\_CharmBaryons.pdf](http://www-cdf.fnal.gov/physics/new/bottom/100701.blessed-Charm_Baryons/cdf10260_CharmBaryons.pdf)



# Backup

# Systematic Uncertainties

Source	$\Delta m(\Sigma_c(2455)^0)$	$\Gamma(\Sigma_c(2455)^0)$	$\Delta m(\Sigma_c(2520)^0)$	$\Gamma(\Sigma_c(2520)^0)$
Resolution	-	0.45 MeV/ $c^2$	-	0.70 MeV/ $c^2$
Mass Scale	0.12 MeV/ $c^2$	0.20 MeV/ $c^2$	0.12 MeV/ $c^2$	0.20 MeV/ $c^2$
Fit Model	0.02 MeV/ $c^2$	-	0.11 MeV/ $c^2$	1.16 MeV/ $c^2$
Sum	0.12 MeV/ $c^2$	0.49 MeV/ $c^2$	0.16 MeV/ $c^2$	1.37 MeV/ $c^2$
Statistical	0.03 MeV/ $c^2$	0.11 MeV/ $c^2$	0.43 MeV/ $c^2$	1.82 MeV/ $c^2$

Source	$\Delta m(\Sigma_c(2455)^{++})$	$\Gamma(\Sigma_c(2455)^{++})$	$\Delta m(\Sigma_c(2520)^{++})$	$\Gamma(\Sigma_c(2520)^{++})$
Resolution	-	0.40 MeV/ $c^2$	-	0.69 MeV/ $c^2$
Mass Scale	0.12 MeV/ $c^2$	0.20 MeV/ $c^2$	0.12 MeV/ $c^2$	0.20 MeV/ $c^2$
Fit Model	0.02 MeV/ $c^2$	-	0.11 MeV/ $c^2$	1.16 MeV/ $c^2$
Sum	0.12 MeV/ $c^2$	0.45 MeV/ $c^2$	0.16 MeV/ $c^2$	1.36 MeV/ $c^2$
Statistical	0.04 MeV/ $c^2$	0.13 MeV/ $c^2$	0.56 MeV/ $c^2$	2.12 MeV/ $c^2$

Source	$\Delta m(\Lambda_c(2595)^+)$	$h_2^2$	$\Gamma(\Lambda_c(2595)^+)$	$\Delta m(\Lambda_c(2625)^+)$
Resolution	0.06 MeV/ $c^2$	0.03	0.22 MeV/ $c^2$	-
Mass Scale	0.12 MeV/ $c^2$	0.03	0.20 MeV/ $c^2$	0.12 MeV/ $c^2$
$\Delta m, \Gamma$ of $\Sigma_c(2455)$	0.15 MeV/ $c^2$	0.06	0.36 MeV/ $c^2$	-
Sum	0.20 MeV/ $c^2$	0.07	0.47 MeV/ $c^2$	0.12 MeV/ $c^2$
Statistical	0.14 MeV/ $c^2$	0.04	0.30 MeV/ $c^2$	0.04 MeV/ $c^2$